

COMETS: DATA, PROBLEMS AND OBJECTIVES

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228

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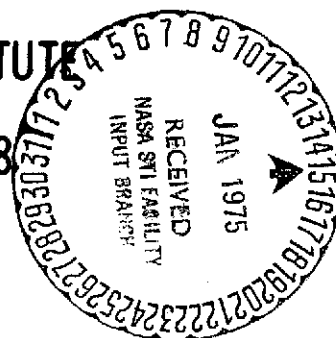
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## N O T I C E

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## COMETS: DATA, PROBLEMS AND OBJECTIVES

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ABSTRACT: A highly abridged review of new relevant results from the observations of Comet Kohoutek (1973f) is followed by an outline summary of our basic knowledge concerning comets, both subjects being confined to data related to the nature and origin of comets rather than the phenomena (for example, plasma phenomena are omitted).

The discussion then centers on two likely places of cometary origin in the developing solar system, the proto-Uranus-Neptune region versus the much more distant fragmented interstellar cloud region, now frequented by comets of the Öpik-Oort cloud. The Comet Kohoutek results add new insights, particularly with regard to the parent molecules and the nature of meteoric solids in comets, to restrict the range of the physical circumstances of comet formation.

A few fundamental and outstanding questions are asked and a plea made for unmanned missions to comets and asteroids in order to provide definitive answers as to the nature and origin of comets, asteroids and the solar system generally.

### A FEW OF THE MAJOR ADVANCES IN COMET KNOWLEDGE

#### FROM OBSERVATIONS OF COMET KOHOUTEK, 1973f

The first radio observations of a comet leading to the discovery of the new parent molecules, methyl cyanide ( $\text{CH}_3\text{CN}$ ) were made by Ulrich and Conklin (1973) and hydrogen cyanide ( $\text{HCN}$ ) by Snyder, Buhl

and Huebner (1974a) both near 3-mm wavelength. The latter investigators (1974b) find that HCN contributes approximately one percent and  $\text{CH}_3\text{CN}$  approximately two percent of the cometary molecular loss rate near perihelion, the total exceeding 100 T/sec. They find evidence for radiation from ethyl alcohol ( $\text{C}_2\text{H}_6\text{OH}$ ) at 86.247GHz and possibly SiO at 86.242GHz. Biraud et al (1973) and Turner (1973) observed OH in absorption in two 18-cm lines while Rydbeck et al. (1974) and Black et al (1974) observed CH in emission at 9-cm wavelength. Hobbs, Maran and Webster (1974) observed continuum radiation at 3.7 and 2.8 cm, the first from a comet.

Lew and Heiber (1973) and Herzberg and Lew (1974) made a major step forward by identifying  $\text{H}_2\text{O}^+$  bands which were measured by Benevenuti and Wurm (1974) and by Wehinger Wycoff and Herbig (1974). Definitive studies of this vital ion should solidify our knowledge of the abundance and behavior of  $\text{H}_2\text{O}$ , apparently the most abundant and controlling material in comets.

From the Ames-NASA Convair 990, Blamont and Festou (1974) established that the OH radical has a half-life of only 8.5 h at 0.62 a.u. solar distance, an order of magnitude shorter than previously estimated. They thus find the radical being created within 15,000 km of the nucleus at a total rate of  $10^{29}$  OH/sec at 0.62 a.u. post perihelion, January 15, 1974. This result, as a minimum rate loss for  $\text{H}_2\text{O}$  atoms, confirms beautifully the conclusion of Code and Savage (1972) by  $\text{La}$  measurements from the OAO that Comet Bennett 1970II was losing  $10^{29}$   $\text{H}_2\text{O}$ /Ster/sec at a comparable solar distance with an absolute magnitude about 2.5 mag. brighter than Kohoutek.

The prediction of an anti-tail by Sekanina (1973) and its observation near perihelion first by Gibson from Skylab (1973), then by Ney and Ney (1974) in the infrared, followed by many observations in the post perihelion period, establishes the expulsion of large particles ( $\sim 1$  mm) from the nucleus. Even though Kohoutek was not a "dusty" comet, based on its color (Shipman, 1974) and the appearance of its visual spectrum, its red continuum (Andrillat, 1973)/<sup>was</sup>very strong and the comet was excessively bright in the infrared as measured by many observers. The observed microwave continuum probably represented thermal radiation from large particles, perhaps icy grains.

There is no time here to discuss the invaluable results from observations of  $\text{L}\alpha$ , and the far ultraviolet from Mariner 10, Skylab and rockets, the numerous infrared measurements and the extensive classical observations. Comet Kohoutek has been the most thoroughly observed comet in history. The completeness of the spectral record from He I at  $\lambda 304 \text{ \AA}$  (negative result) to the cm-wave radio region will provide answers to a number of critical questions concerning comets. In particular these extensive data will give us the first precise measure of the mass ratio of volatile ices to meteoric solids, a ratio that is vital in determining the nature and place of origin. The extensive data including a number of important negative results ( $\text{NH}_3$ ,  $\text{CH}_4$ , He and acetone), will certainly add other knowledge to restrict substantially the possibilities regarding the origin of comets.

## BASIC FACTS AND DEDUCTIONS

### ABOUT THE NATURE OF COMETS

In discussing the role of comets in the evolution of the solar system we may confidently assume the following basic facts and deductions about their character:

A. Comets are members of the solar system. No evidence exists for orbits of interstellar origin (Marsden and Sekanina, 1973).

B. Comets have been stored for an unknown length of time in very large orbits in the Öpik-Oort cloud out to solar distances of tens of thousands of astronomical units (Öpik, 1932, Oort, 1950). Perhaps  $10^{11}$  comets with a total mass comparable to that of the Earth still remain, as Oort suggested.

C. The basic cometary entity is a discrete nucleus (rarely, if ever, double) of kilometer dimensions consisting of ices and clathrates, including specifically  $H_2O$ ,  $CH_3CN$ ,  $HCN$ ,  $CO_2$  and probably  $CO$ . Other parent molecules of the abundant H, C, N and O atoms mixed in an unknown fashion with a comparable amount of heavier elements as meteoric solids must occur in comets because of the observed radicals, molecules and ions,  $C_2$ ,  $C_3$ ,  $CH$ ,  $CN$ ,  $NH$ ,  $NH_2$ ,  $N_2^+$ ,  $CO^+$  and  $CH^+$  (Whipple, 1950, 1951. Delsemme and Swings, 1952, Swings, 1965).

D. Cometary meteoroids are fragile and of low density (McCrosky, 1955, 1958. Jacchia, 1955).

E. The comet nuclei as a whole must have never been heated much above a temperature of about  $100^\circ K$  for a long period of time, otherwise new comets could not show so much activity at large solar distances (Kohoutek, 1973f, for example). Possible internal heating

by radioactivity and temporary external heating, by supernovae for example, is not excluded.

F. Comets were formed in regions of low temperature, probably much below 100°K.

G. Comet nuclei are generally rotating, but in no apparent systematic fashion and with unknown periods in the range from about 3h to a few weeks, based on non-gravitational motions and the delayed jet action of the icy nucleus.

H. The nuclei, at least of three tidally split comets, show evidence of a weak internal compressive strength the order of  $10^4 - 10^6$  dyne cm<sup>-3</sup> (Öpik, 1966) and evidence of little internal cohesive strength.

I. The surface material of active comets must be extremely friable and porous to permit the ejection by vapor pressure of solids and ices at great solar distances. The evidence of clathrates by (1952) Delsemme and Swings/coupled with the probable ejection of ice grains at great solar distances (Huebner and Weigert, 1966) support this deduction.

The following probable limits of cometary knowledge or negative conclusions appear valid:

1. Roughly a solar abundance of elements may reasonably be assumed for the original material from which comets evolved. Note Millman's (1972) evidence regarding the relative abundances of

Na, Mg, Ca and Fe in cometary meteor spectra and the solar value of the  $^{12}\text{C}/^{13}\text{C}$  ratio measured by Stawikowski and Greenstein (1964, C. Ikeya, 1963I) and Owen (1973, C. Tago-Sato-Kosaka, 1969 IX).

2. The material in the region of comet formation (with roughly solar abundances of elements) could not have cooled slowly in quasi-equilibrium conditions from high temperatures. The significant abundances of CO, CO<sub>2</sub>, C<sub>2</sub>, C<sub>3</sub> and now CH<sub>3</sub>CN and HCN in comets along with the low density and friability of the cometary meteoroids indicate non-equilibrium cooling in which the carbon did not combine almost entirely into CH<sub>4</sub> and the meteoroids generally did not have time to aggregate into more coherent high-density solids before they agglomerated with ices.

3. The existence of an original plane of formation of comets beyond some 3000 to 5000 a.u. appears to be unknowable. The perturbations by passing stars would have so disturbed the orbits that the lack of evidence for a common plane in the motions of new comets tells nothing about the place or plane of origin (Oort, 1950) (Note exception in 4 below).

4. That the comets formed concurrently with the solar system some  $4.6 \times 10^9$  years ago is an assumption based on the lack of a tenable theory for more recent or current formation. The lack of evidence for a common plane of motion implies an origin remote in time or, if recent, no common plane of origin.

5. The highly variable ratio of dust to gas observed from comet to comet proves a large variation in particle-size-distribution



but has not yet been shown, to measure a true variation in the dust/gas mass ratio. P/Encke, for example, shows a low dust/gas ratio in its spectrum but has contributed enormously to the interplanetary meteoroid population.

#### THE ROLE OF COMETS IN THE ORIGIN OF THE SOLAR SYSTEM\*

The above evidence points conclusively to the origin of comets by the growth and agglomeration of small particles from gas (and dust?) at very low temperatures. But where? If concurrently with the origin of the solar system (and necessarily associated with it gravitationally) two locations in space are, a priori, possible:

I. In the other regions of the forming planetary system beyond proto-Saturn (Kuiper, 1951; Whipple, 1951), or

II. In interstellar clouds gravitationally associated with the forming solar system but at proto-solar distances out to a moderate fraction of a parsec, that is to say, in orbits like those in the Öpik-Oort cloud of present day comets (Whipple, 1951; McCrea, 1960; Cameron, 1962).

\* The reader is referred to V. S. Safronov's comprehensive book "Evolution of the Protoplanetary Cloud and Formation of the Earth and Planets" (Izdatel'stvo "Nauka, Moscow, 1969; translated into English by the Israel Program for Scientific Translation and published by NASA, 1972) for a modern development of the Kant-LaPlace concept including the important contributions by O. J. Schmidt, and a general

historical background of this general concept. For less general special treatments see Kuiper (1951), Urey (1952), Levin (1958), Cameron (1962), Whipple (1964), Alfvén and Arrhenius (1970 a,b), Nobel Symposium 21 (1972) and Öpik (1973). For concepts of comet or solar system origin deviating from the "classical," see Souček (1946), Lyttleton (1948), Whipple (1948 a,b), Trulsén (1972), O'Dell (1973) and especially Cameron and other contributors to the Symposium at Nice "On the Origin of the Solar System" (1972, Edition du Centre National de la Recherche Scientifique 15, Quai Anatole France, Paris).

There can be little doubt that comets were the building blocks for the great outer planets, Uranus and Neptune. The mean densities of these planets (Ramsey, 1967) are consistent with their origin largely from the accretion of comets, assumed to consist of the compounds possible, excluding  $H_2$ , in a solar mix of elements. This process of building Uranus and Neptune is precisely analogous to building the terrestrial planets from planetesimals. Temperature was the controlling factor, being too high within the orbit of proto-Jupiter for water to freeze. For this reason Oort's (1950) suggestion that the comets formed within the Jupiter region appears unlikely because asteroids clearly formed there. Similarly, Öpik's requirement for solid  $H_2$  in the proto-Jupiter region appears untenable. Nevertheless, Oort's idea that comets were thrown out from the inner

regions of the solar system by planetary perturbations is highly significant.

Thus the possible origin of the presently observed comets in the Uranus-Neptune region rests solely on the premise that the major planets (or proto-planets) could indeed throw the comets into stable orbits with aphelia out to some 50,000 a.u. or more. The low efficiency of the process is only restrictive in the sense that too much angular momentum may be required of the outer planets to accomplish the feat successfully. Approximately a solar mass of comets in large orbits appears to be required as an end product but a hundred solar masses may originally have been involved. Öpik (1965, 1973) is doubtful about the process unless the comets formed near Jupiter; Everhart (1973) finds it highly unlikely while Levin (1972) provides the angular momentum from proto-Uranus and proto-Neptune by forming these planets at very great solar distances (up to 200 a.u.) from a very large nebular mass and drawing them into their present orbits by the ejection of comets (mostly to infinity).

Everhart's doubts may possibly be removed if the space density of comets originally fell off rapidly with solar distance and that the supply at great distances (Marsden and Sekanina, 1973) has been replenished by those in smaller orbits, more stable against stellar perturbations. Indeed Öpik (1932) showed that stellar perturbations will systematically increase perihelion distances to remove the comets from the region of perturbation by the outer planets. The

number of comets thrown into the inner solar system during the immediate post-nebula period could have been significant and may account for major crater formation on the Moon (see Hartmann, 1972) and volatiles on the terrestrial planets (Lewis, 1974).

Alternative II, of forming the comets directly in the orbits of the Öpik-Oort Cloud is highly attractive except for the difficulty of agglomerating kilometer sized bodies in the low-density fragmented interstellar clouds. Such a possibility must be demonstrated before one can accept the tempting solution to the problem. Öpik (1973) finds the process quite impossible.

Let us now look to the comets themselves to see whether their structure can help us distinguish between the two possible regions of origin. Most conspicuous are the numerous carbon radicals, molecules and ions not in low-temperature equilibrium with excess hydrogen. The gas, if once hot, could not have cooled slowly. Note too the friability and low density ( $0.5$  to  $< 0.01$  gm/cm<sup>3</sup>) for meteoric "solids." Sekanina (private communication) finds evidence that for Comet Kohoutek the larger grains tend to shrink appreciably in a period of a few days. We must conclude that the ices, earthy material and clathrates were all accumulated simultaneously at very low temperatures.

More specifically, the ices, clathrates and "solids" collected together intimately in such a fashion that earthy molecules were somewhat bonded together in order to provide some degree of physical strength after the ices sublimated. Note that any sintering process

to make the earthy grains coherent physically would remove the highly volatile substances necessary to provide the activity of Comet Kohoutek and other comets at great solar distances where the vapor pressure of  $H_2O$  is negligible. Thus the process of grain growth must have involved the "whisker" type of growth, commonly observed in laboratory crystals. We can confidently visualize a comet as a complex lacy structure of "whiskers" and "snowflakes" that grew atom-by-atom and molecule-by-molecule while highly volatile molecules were trapped as clathrates.

The temperature could have been sufficiently low for such cometary growth anywhere in space beyond perhaps 30 to 50 a.u. from the center of the proto-solar-system. Levin's (1972) concept of comet growth up to 200 a.u. is entirely consistent with such growth, as is alternative II, fragmented interstellar clouds at far greater distances. Safronov and Levin's requirement of excessive material (perhaps 30 - 100 times the present-day mass of Uranus and Neptune) to provide a reasonably rapid growth rate for Uranus and Neptune confirms Öpik's vehement denial that fragmented interstellar clouds may be capable of producing comets. Careful analysis of grain growth rates under imaginative sets of assumptions as to the nature and stability of such clouds is clearly needed. Note that a comet does not appear to be an aggregate of interstellar grains if, indeed, these grains are solids covered with icy mantles. Such grains would not cohere when exposed to solar radiation sublimating the ices.

At the present, then we have no criterion to identify the unique region in space where comets formed, if indeed they all formed in the same general region. We need more precise knowledge concerning the identity and abundances of the more volatile parent molecules. Did  $\text{CH}_4$ , CO, Ar or Ne, for example, actually freeze out in comets? As Lewis (1972) shows the mass percentages of such volatiles can be used as thermometers. Even the dimensions of comet nuclei are uncertain, while we have no knowledge whatsoever of their detailed structure. Are they layered? Do they contain "pockets" of ices or "pockets" of dust? How fast do they rotate? What produces comet bursts in luminosity? What causes "new" comets to split?

Furthermore, we do not know whether comets generally or indeed any comets contain cores of asteroidal nature. It is tempting to identify many of the Apollo or Earth-orbit crossing asteroids, as "burned out" comets. Proof of a truly asteroidal core for an old comet would require a further knowledge of the chemistry and structure of the core to ascertain whether meteoric material collected first or whether radioactive heating drove out the volatiles. Such knowledge would, of course, be invaluable in ascertaining the physical and chemical circumstances of the origin. No definitive answer is likely without such data.

It is clear that far more ground-based and space-based research on comets is necessary. C Kohoutek has shown that a massive attack on one comet can produce extraordinary results. There are too many comets to permit an over-all observational attack on each one. Nevertheless we need to accumulate data on all observable comets. A reasonable program is to institute massive observing programs from time to time for especially selected comets while accumulating basic data for all comets.

Only space missions to comets can give us the "quantum jump" in knowledge necessary to solve the most fundamental problems of comets. Equally we need to study a few asteroids at their surfaces to understand their nature and to identify the sources of meteorites. Because meteorites have given us extraordinary insight regarding early conditions in the developing solar system, we can expect asteroid space missions to answer some basic direct questions, while "calibrating" our laboratory data on meteorites. Furthermore the extraordinary successes in exploring the Moon and Mars have given us limited data concerning the early phases of solar system formation because these bodies have been severely altered since they were originally agglomerated.

Space missions to comets and to asteroids are the essential next steps towards understanding how the solar system came into being. Such missions are entirely feasible in the present state of our space technology.\*

\* The following references are related to space missions to comets and asteroids:

Report of the Comet and Asteroid Mission Study Panel, NASA TM X-64677, 1972.

Alfvén, H. and Arrhenius, G. 1970. Mission to an Asteroid. Science, 167, 139.

Lüst, Reah, "Cometary Probes", Space Science Reviews, 10 (1969), 217-299

The 1973 Report and Recommendations of the NASA Science Advisory Committee on Comets and Asteroids, NASA TM-X-71917, 1973.

Physical Studies of Minor Planets (NASA SP267) ed. T. Gehrels, NASA, 1971.

Proceedings of the Cometary Science Working Group, ed. D. L. Roberts, IIT Research Institute, 1971.

Comets, Scientific Data and Missions, ed. E. Roemer and G. P. Kuiper, Lunar and Planetary Laboratory, Univ. of Arizona, 1972.

Nobel Symposium No. 21, From Plasma to Planet, ed. Aina Elvius, Almquist and Wiksell, Stockholm, 1972.

On the Origin of the Solar System, ed. Hubert Reeves, Centre National de la Recherche Scientifique, Paris, 1972.

Comets and Asteroids, Strategy for Exploration, NASA TMX-64677, 1972.



- Lyttleton, R. A., 1948, Mon. Not. Roy. Ast. Soc., 108, 465.
- Marsden, B. G. and Sekanina, Z., 1973, A. J., 78, 1118-1124.
- McCrea, W. H., 1960, Proc. Roy. Soc. (London), A256, 245-266.
- McCrosky, R. E., 1955, A. J., 60, 170.
- McCrosky, R. E., 1958, A. J., 63, 97-106.
- Millman, P. M., 1972, Nobel Symposium 21, From Plasma to Planet, ed. A. Elvius, 156-166, Almquist and Wiksell, Stockholm.
- Ney, E. P. and Ney, W. F., 1974, I.A.U. Circ. 2616.
- Nobel Symposium 21, 1972, From Plasma to Planet, ed. A. Elvius, Almquist and Wiksell, Stockholm; Wiley & Sons, N.Y., London, Sydney.
- O'Dell, C. R., 1973, Icarus, 19, 137-146.
- Oort, J. H., 1950, Bull. Astr. Inst. Neth., 11, 91-110.
- Öpik, E., 1932, Proc. Amer. Acad. Arts and Sci., 67, 169-183.
- Öpik, E. J., 1966, Irish Ast. J., 7, 141-161.
- Öpik, E. J., 1963, Advances in Astronomy and Astrophysics, ed. Z. Kopal, Academic Press, 2, 219-262.
- Öpik, E. J., 1965, Mem. Soc. Roy. Sci. Liège, Ser. 5, 12, 523-574.
- Öpik, E. J., 1973, Ap. & Sp. Sci., 21, 307-398.
- Owen, T., 1973, Ap. J., 184, 33-43.
- Ramsey, W. H., 1967, Planetary and Space Sci., 15, 1609-1633.
- Rydbeck, O.E.H., Elldér, J. and Irvine, W. M., 1974, I.A.U. Circ. 2618.
- Shipman, H. L., 1974, I.A.U. Circ. 2632.
- Skylab, 1973, I.A.U. Circ. 2614.
- Sourek, J., 1946, Mem. and Obs. of Czech. Ast. Soc. Prague, No. 7.

## REFERENCES

- Alfvén, H. and Arrhenius, G., 1970a, *Ap. & Sp. Sci.*, 8, 338-421.
- Alfvén, H. and Arrhenius, G., 1970b, *Ap. & Sp. Sci.*, 9, 3-33.
- Andrillat, Y., 1973, *I.A.U. Circ.* 2610.
- Benvenute, P. and Wurm, K., 1974, *Astron. and Astrophys.*, in press.  
(*I.A.U. Circ.* 2628).
- Beraud, F., Bourgois, G., Crovisier, R., Fillit, R., Gérard, E. and Kazes, I., 1973, *I.A.U. Circ.* 2607.
- Black, J. H., Chaisson, E. J., Ball, J. A., Penfield, H. and Lilley, A. E., 1974, *I.A.U. Circ.* 2621.
- Blamont, J. and Festou, M., 1974, *Comptes Rend.*, in press.
- Cameron, A. G. W., 1962, *Icarus*, 1, 13-69.
- Code, A. D. and Savage, B. D., 1972, *Science*, 177, 213-221.
- Delsemme, A. H. and Swings, P., 1952, *Ann. d'Astrophys.*, 15, 1-6.
- Everhart, E., 1973, *A.J.*, 73, 329-337.
- Hartmann, W. K., 1972, *Ap. & Sp. Sci.*, 17, 48-64.
- Herzberg, G. and Lew, H., 1974, *I.A.U. Circ.* 2618.
- Hobbs, R. W., Maran, S. P. and Webster, Jr., W. J., 1974, *I.A.U. Circ.* 2626.
- Heubner, W. and Weigert, A., 1966, *Z. f. Astrophys.*, 64, 185-201.
- Jacchia, L. G., 1955, *Ap. J.*, 121, 521-527.
- Kuiper, G. P., 1951, *Astrophysics*, ed. J. A. Hynek, McGraw-Hill Co., N.Y., London, Ch. 8.
- Levin, B., 1958, *L'Origine de la Terre et des Planets*, Moscow.
- Levin, B., 1972, "On the Origin of the Solar System," a symposium at Nice, Centre National de la Recherche Scientifique, Paris.
- Lew, H. and Heiber, I., 1973, *J. Chem. Phys.*, 58, 1246.

- Snyder, L., Buhl, V. and Huebner, W., 1974b, A.A.S. DPS, Abst., April 1974.
- Stawikowski, A. and Greenstein, J. L., 1964, Ap. J., 140, 1280.
- Swings, P., 1965, Quart. J. Roy. Ast. Soc., 6, 28-69.
- Trulsen, J., 1972, Nobel Symposium 21, From Plasma to Planet, ed. A. Elvius, 179-192, Almquist and Wiksell, Stockholm.
- Ulrich, B. L. and Conklin, E. K., 1973, I.A.U. Circ. 2607.
- Urey, H. C., 1952, The Planets, Their Origin and Development, 245 pp. Yale Univ. Press, New Haven.
- Wehinger, P. A., Wycoff, S., Herbig, G. H., Herzberg, G. and Lew, H., 1974, Ap. J. Let., in press.
- Whipple, F. L., 1950, Ap. J., 111, 375.
- Whipple, F. L., 1951, Ap. J., 113, 464-474.
- Whipple, F. L., 1948a,b, a. Sci. Amer., 178, 34-45; b. Harv. Obs. Mon., No. 7, 109-142.